WORK ROLL ROUGHNESS TOPOGRAPHY AND STRIP CLEANLINESS DURING COLD ROLLING AUTOMOTIVE SHEET*

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Abstract
A point of great importance in the cold rolling process for automotive sheet is the cleanliness of the strip, particularly critical in case of batch annealing with no degreasing line or inefficient cleaning before continuous lines. In this specific cases, pollution of the strip surface could be prohibitive when rolling in the early stands of tandem mill with conventional forged work rolls as ground. The strip cleanliness strongly deteriorates during rolling particularly with high roughness rolls: iron fines are generated at the strip surface due to friction and stick on the sheet. It is well known that chrome plating on ground forged rolls in the early stands improve the strip cleanliness. This paper summarizes the results of 3D surface roughness topography studies on forged work rolls, with and without chrome plating, combined with sheet cleanliness measurement during rolling. It shows that a well determined topography has to be obtained on the work rolls used in early stands in order to roll in the mixed lubrication regime, as described by the Stribeck curve, minimizing the friction coefficient and therefore optimizing the cleanliness of the rolled sheet. The main roll roughness parameters to take into account for that purpose are the roughness level Sa, and even more, the Kurtosis parameters Sk, Spk, Svk and Ssk. The ideal surface morphology promotes deep valleys to the detriment of peaks, leading to a roll surface capable of retaining/trapping oil in the valleys, while peaks are minimized, thus reducing the friction in the roll bite and the amount of iron fines produced. To achieve this objective, new grinding wheel technologies are currently developed, in dialogue with wheel manufacturers, to create such ideal morphology of roughness well adapted to HSS forged rolls.
Keywords: Surface roughness; Sheet cleanliness; Forged HSS rolls; Cold rolling..

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1 INTRODUCTION

Using forged HSS rolls in a cold tandem mill for automotive sheet allows to suppress the operation of roll chrome plating which is expensive and deleterious for environmental reasons while keeping longer campaigns in the mill [1], [2], [3], [4]. However, as standard forged rolls non chrome plated, the suppression of chroming on the work rolls in early stands (stand 1 and stand 2) leads to a degradation of around 10 to 15% of rolled sheet cleanliness compared with chrome plated rolls.
The presence of iron fines on the surface of the cold rolled sheet is strongly dependent on the rolling conditions in the early stands and is critical for visible automotive parts when batch annealing is applied immediately after cold rolling with no degreasing or inefficient cleaning section line in other lines [5], [6]. This issue can affect subsequent rolling process steps and/or product quality such as:

- inadequate zinc adherence,
- excessive dross formation in hot dip galvanizing lines,
- surface defects in temper mill (imprints),
- painting issues.

The purpose of the paper is to analyze the reasons of such cleanliness degradation when the work rolls are not chrome plated in the early stands and to define the good parameters to use in these stands forged HSS rolls without chroming.

2 MATERIAL AND METHODS

2.1 Rolled sheet cleanliness measures

Scotch Tape (ST) or Reflection Tape (RT) method is a common and easy measurement of sheet cleanliness in all industrial cold mills and accepted as a qualification criterion by final users for automotive sheet (well correlated to level of strip surface pollution).
After cold rolling, an adhesive tape is applied to the strip and after removing the tape it is stuck on a white paper.

A light source is directed to the tape and the reflected light is detected. The fraction reflected light is a measure for the degree of strip cleanliness:

- If 100% of the light is reflected, the tape is entirely transparent.
- If 0% of the light is reflected, the tape is entirely black

The higher the fraction of reflected light, the better the strip cleanliness is.
Typical reflection values after cold mill are between 40 and 80% depending on rolling conditions and rolled product.

2.2 In use parameters influencing sheet cleanliness

2.2.1 Operational parameters [5]:

Rolling speed:
Higher rolling speed leads to increase the strip cleanliness: the speed leads to the building of a hydrodynamic lubricant film in the roll bite and a subsequent decrease of the friction coefficient.

Reduction:
In the first stand(s) big metal removal due to high strip thickness and longer sliding lengths increase friction surface and result in a lower strip cleanliness.
On the last stands, roll bite surface reduces a lot and lubrication is better due to the higher rolling speed: this results in a better strip cleanliness.

Rolling force:
In the first stand(s), specific roll force is often higher and strip cleanliness decreases.

2.2.2 Coolant system [6], [7]:

Cooling efficiency:
An efficient cooling system with adapted flow, especially in the early stands, allows to decrease the interfacial temperature in the rolling gap and consequently help to keep strip cleanliness at a good level by avoiding overheating.

Type of emulsion:
Chemical and physical properties of the rolling emulsion also are important to consider in order to decrease the friction coefficient during rolling and therefore to improve the strip cleanliness. Main parameters are the size of oil droplets, the oil concentration and additive elements in order to keep consistent oil film in the rolling gap.

2.2.3 Surface topography of work roll:

In a first approach, the strip cleanliness decreases when work roll surface roughness increases.

2.3 Surface roughness topography

Two investigation methods have been applied to measure the surface roughness topography of the rolls [8]:
-mechanical roughness for 2D profile following norm ISO 4287 (figure 1);
-replicas allowing 3D surface optical measurements following norm ISO 25178 (Figure 2).

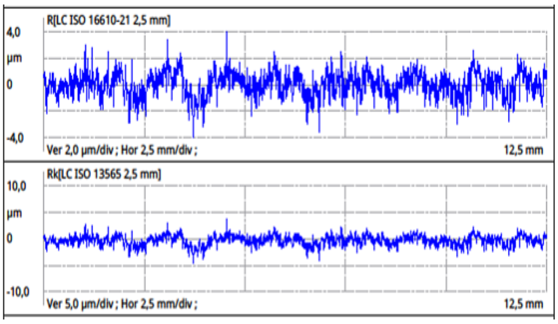

Figure 1. 2D roughness profile measured with mechanical device.

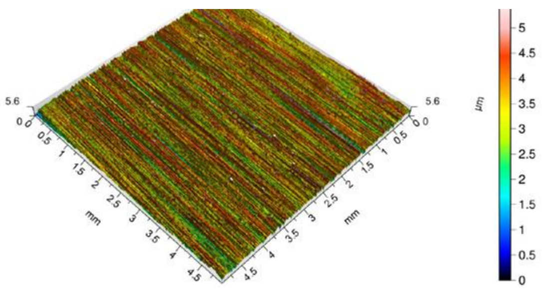

Figure 2. 3D roughness surface measured on replicas with optical device.

With both measurement approaches, the main functional roughness parameters acting on friction coefficient during cold rolling have been checked, i.e.:

- Average roughness profile Ra (µm) or average roughness surface Sa (µm) which is useful for monitoring an established manufacturing process such as grinding.

- Skewness or asymmetry of the profile Rsk (µm) or the surface Ssk (µm). Negative skew indicates a predominance of valleys (plateau profile) and is a criterion for good bearing surface. Positive skew is seen on surface with predominance of peaks.

- Abbott curve: bearing area of the roughness or core roughness profile Rk (µm) or surface Sk (µm): after the initial running in period this part of the surface carries the load and most closely contacts the mating surface.
- Abbott curve: Peak height above the core roughness profile Rpk (µm) or surface Spk (µm). These peaks will typically be worn off (or down) during the run-in period for a part. Generally, it would be desired to have a fairly small Rpk (Spk).
- Abbott curve: Valley depth below the core roughness profile Rvk (µm) or surface Svk (µm). These valleys will retain lubricant in a functioning part.

The figure 3 shows the relations between the average roughness (Ra, Sa) obtained and the functional 2D roughness profile parameters (Rk, Rpk, Rvk) and 3D roughness surface parameters (Sk, Spk, Svk). It shows that, if the average roughness profile Ra is the easiest and simplest way to monitor an established rolling process, the replicas method with 3D surface optical measurements allows a more precise approach of the surface topography and therefore to adjust more finely the grinding parameters acting on friction coefficient during cold rolling.

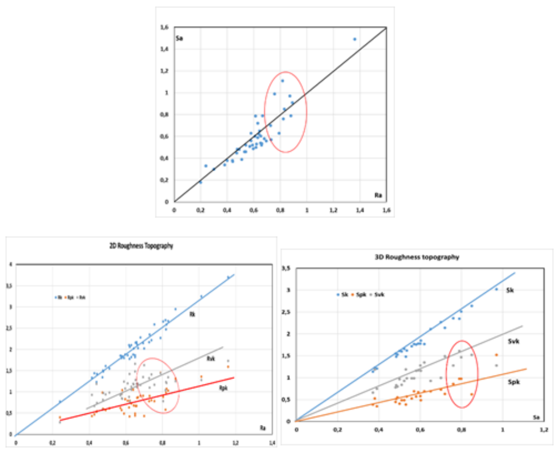

Figure 3. Relationships between 2D roughness parameters (µm) and 3D roughness parameters (µm).

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3 RESULTS AND DISCUSSION

3.1 Rolled sheet cleanliness

Figure 4 and 5 show the effect to chrome plate the work rolls in early stands on the rolled sheet cleanliness for two cold rolling mills: stand 2 chrome plated or not in a 6hi five stands tandem mill with stand 1 chrome plated; stand 1 chrome plated or not in a 4Hi five stands tandem mill with stand 2 chrome plated.

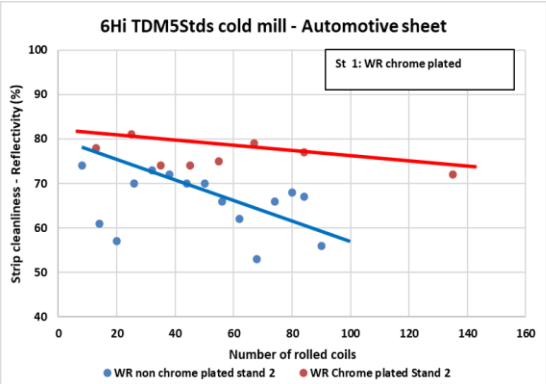

Figure 4. Sheet cleanliness improvement with chrome plating rolls in early stands of a 6Hi five stands cold tandem mill

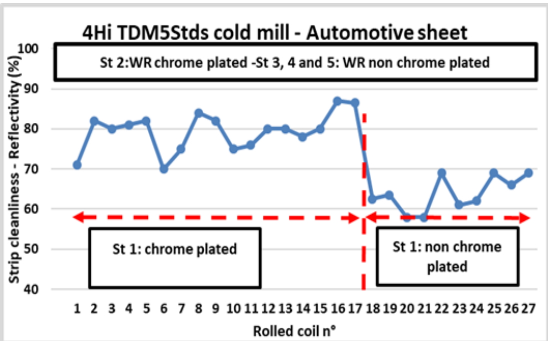

Figure 5. Evolution of sheet cleanliness when rolling with and without chrome plating rolls in stand 1 of a 4Hi five stands cold tandem mill.

When rolling with standard forged rolls (3 to 5% chromium grades) non chrome plated in early stands, the cleanliness of the rolled sheet (measured at the exit of the last stand) decreases. Chroming the work rolls in stands 1 and 2 of a cold Tandem mill improves the cleanliness of the rolled sheet of about 10 to 15% and maintains the same level of cleanliness during longer rolling campaign.

Table 1 gives the results of impurities analysis on a sampling of a cold rolled sheet taken on the exit of the last stand of a five stands cold tandem mill with the configuration of the stands: Stand 1, 3, 4 and 5 non chrome plated work rolls; Stand 2 chrome plated work rolls. The reflectivity measured on the sampling was 70%.
Surface Carbon content on the sampling has been measured by combustion in O_2 of five replicates.

Chemical analysis of sheet surface (mg/m²)	
Average Carbon	34.9
Iron fines	56
Molybdenum	< 0.2

Table 1. Sheet surface analysis of impurities in a 4Hi Five stands cold Tandem mill: rolls non chrome plated in stand 1 and chrome plated in stand 2.

The SEM-EDS analysis of the particles sticking to the scotch tape surface indicates a percentage of iron of 99.54% with low manganese content (0.34%) similar to the steel composition (figure 6). No molybdenum particles have been detected from the roll.

This analysis clearly shows that the pollution of the rolled sheet is due to a mixture of oil and iron fines coming from the strip surface and progressively sticking on the sheet.

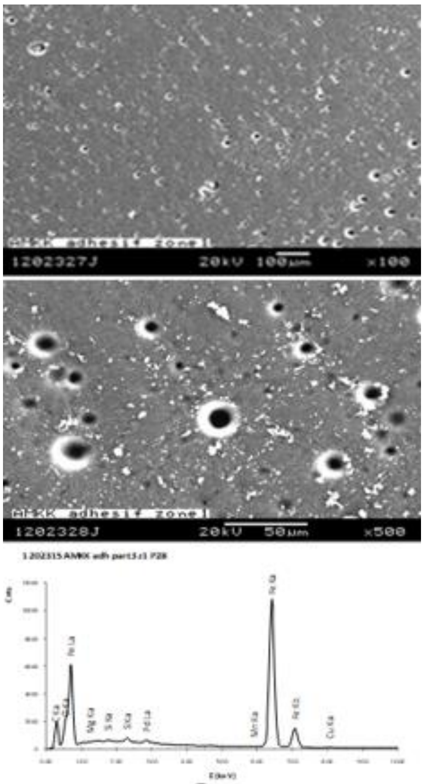

Figure 6. SEM-EDS characterization of scotch tape surface

Moreover, it is well known that reflectivity is directly correlated to iron fines on strip surface (figure 7).

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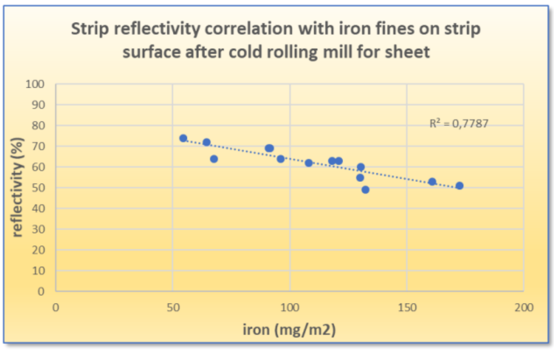

Figure 7. Cleanliness reflectivity measurement versus iron fines on strip surface.

3.2 Mechanisms of sheet cleanliness deterioration

3.2.1 Lubrication regimes – Stribeck curve [9], [10].

In the cold rolling process, the lubrication is the specific function dedicated to control the friction between the two bodies in contact (roll and sheet) and consequently the iron fine formation on the rolled sheet.

Friction coefficient between two fluid-lubricated surface contacts is described by the Stribeck curve which is a fundamental concept in the field of tribology. For a given fluid viscosity and load, the curve shows how friction changes with increasing velocity (figure 8).

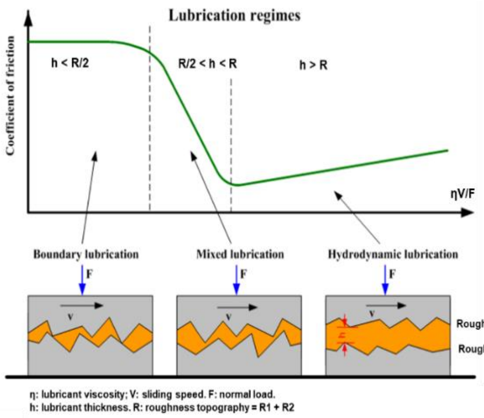

Figure 8. Stribeck curve of friction coefficient between two fluid-lubricated surface contacts.

Three lubrication regimes can be identified on the typical progression of the Stribeck curve:

Boundary lubrication:
Solid surfaces come into direct contact; load is supported mainly by surface asperities, which induces high friction.
This regime is characterized by low sliding speed and high friction leading to severe wear.

Mixed lubrication:
Some asperity contact, load supported by both asperities and liquid lubricant. In this regime, the friction is reduced and wear moderated.

Hydrodynamic lubrication:
Negligible asperity contact, load supported mainly by hydrodynamic pressure.
This regime is characterized by high sliding speed, lower friction and wear is negligible.

3.2.2 Roughness and lubrication regime

For a constant ηV/F ratio, the surface roughness level of the two bodies in contact (R = R1 + R2) plays an important role in the lubrication regime (figure 9) [11].

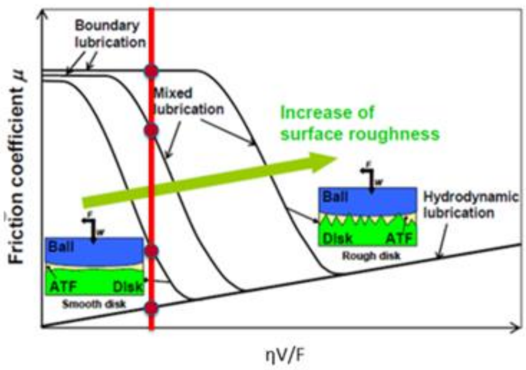

Figure 9. Influence of surface roughness of the bodies in contact on the Stribeck curve.
H: lubricant viscosity, V: sliding speed, F: normal load.

-If the roughness level R is too high, high friction coefficient leads to a lubrication regime too close to boundary lubrication (for same rolling load and speed) while increasing the surface wear of both materials in contact.
-When the boundary lubrication regime takes place, severe wear of both materials and local sticking can occur if the roughness level R is still too high.
-If the roughness is too low, hydrodynamic lubrication will take place with no contact between the two materials and negligible wear.

Therefore, in cold rolling process, the lubrication regime will strongly depend on the roughness surface topography of the work roll and of the rolled sheet, i.e. in a first approach on the roughness level Ra on both work roll and rolled strip.

At the entry of the first stand of the cold rolling mill, the roughness level Ra of the hot strip to be cold rolled is relatively high (around 1.1 to 2.4 µm) and decreases in the rolling gap due to the high elongation.
At the exit of the fore-last stand, the roughness level Ra is around 0.4 / 0.5 µm (last stand textured and strip around 1 µm Ra at the exit).

The roughness level Ra of the work roll is induced by the grinding operation before cold rolling and is generally around 0.8 to 1.2 µm for the first stand in order to have a good grip of the sheet when strip entering in the rolling gap (avoiding skidding). For the next stands, the roughness specification is lower from 0.7 µm to 0.5 µm.
During cold rolling, the roughness level Ra of the work rolls decreases due to wear. Therefore, the back-calculated friction coefficient decreases and also the forward slip leading to more hydrodynamic lubrication regime with rolling issue of sheet slippering when the roll roughness is too low [12].

Cold rolling process must be realized in the right lubrication regime:

-When the cold rolling conditions is too close to boundary lubrication regime, the high friction coefficient induces an increase of contact temperature in the rolling gap and consequently a deterioration of emulsion viscosity, a breakage of the emulsion film and the production of iron fines from the rolled sheet degrading the strip cleanliness.
-In the hydrodynamic lubrication regime, a too low friction coefficient induces rolling issue of sheet slippering with impact of the strip cleanliness and aspect (slip marks).

In addition of roughness level Ra/Sa, the Kurtosis parameters determined from Abbott-Firestone curve have a great influence on the coefficient of friction and therefore the rolled sheet cleanliness [13], [14].

When two surfaces rub together:

-the peak region usually gets worn out (Rpk, Spk)
-the core region bears the load and has influence on the life of the product (Rk, Sk)
-the valley region acts as a lubricant reservoir (Rvk, Svk)

A high bearing core Rk/Sk decreases the contact pressure and therefore the friction coefficient.
The depth of valleys Rvk must be higher than the height of peaks Rpk.
In lubricating conditions, Plateau-like topography of contact surfaces with more negative skewness Rsk reflects in lower friction.

3.3 Effect of chrome plating on surface roughness topography

Figure 10 compares the roughness topography evolution in stand 2 of a five stand tandem mill of standard rolls used as ground with a Ra of 0.6/0.7 µm with standard rolls ground at same Ra level but chrome plated.

In this mill, the chrome plating operation modifies the surface topography of the standard rolls as followed:

- a light decrease of average roughness Ra,
- a light decrease of roughness core Rk,
- a peak height Rpk lower that the valley depth Rvk (ratio Rpk/Rvk < 1) as it is the case of standard roll as ground,
- a decrease of peak height Rpk keeping same valley depth Rvk: this leads to lower the ratio Rpk/Rvk,
- an increase of negative skewness (more plateau-type profile Rsk<0).

This modification of roughness topography by chroming can explain the lower friction coefficient and the sheet cleanliness improvement when rolling with chrome plating rolls in stand 2.

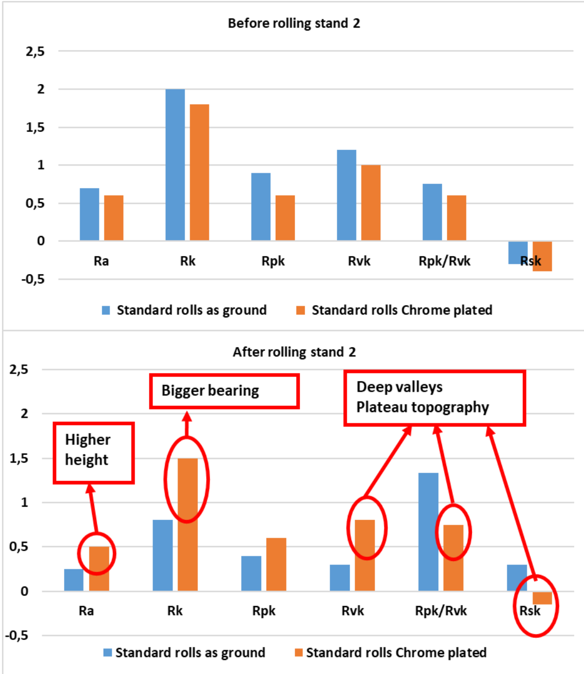

Figure 10. Evolution of the topography of roughness in stand 2 of a five stands tandem mill.

Rolling in stand 2 induces:
- a decrease of Ra,
- a decrease of peak height Rpk.

This evolution of roughness parameters Ra and Rpk should improve the rolled sheet cleanliness. However, in the same time, a modification of roughness topography is observed even for chrome plated rolls:
- a decrease of depth of valleys Rvk,
- a decrease of roughness core Rk,
- a modification of the profile asymmetry from plateau profile (Rsk remaining < 0 for chrome plated rolls) to peak profile (Rsk becoming > 0 for standard rolls not chrome plated).

Moreover, the roughness topography evolution is faster with standard rolls as ground than standard rolls chrome plated with higher wear resistance.
This evolution can explain the big degradation of rolled sheet cleanliness when rolling in stand 2 of this mill with standard rolls as ground.

Figure 11 compares the evolution in stand 1 of a four stands tandem mill of standard rolls used as ground to a level average roughness Ra 0.98 ± 0.13 µm with standard rolls ground at the same level of Ra and chrome plated.

In this case, for this high level of Ra (µm), the chrome plating operation strongly increases the roughness Ra while increasing the depth of valleys Rvk (µm) and promoting a better plateau topography (ratio Rpk/Rvk lower than 1 and skewness factor more negative).

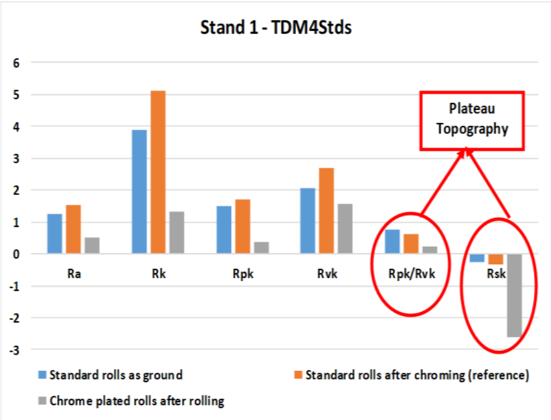

Figure 11. Evolution of the topography of roughness in stand 1 of a four stands tandem mill.

During rolling in stand 1 of the four stands Tandem mill, the peak height Rpk (µm) of the chrome plated rolls strongly decreases while the depth of the valleys Rvk (µm) still remains sufficient to trap the lubricant. It results a skewness factor Rsk more and more negative, promoting a plateau topography and ensuring a continuous lubrication during cold rolling with low friction coefficient and therefore without formation of iron fines and deterioration of rolled sheet cleanliness.

3.4 HSS forged rolls

3.4.1 Main properties of HSS forged rolls

In order to suppress the chrome plating operation on work rolls while keeping at least same campaign length or allowing even longer campaign in the mill, HSS forged rolls have been introduced with success in reduction cold tandem mills, reversing mills, temper/skin pass mills and for various product applications as automotive sheet, AHSS sheet, tin-plate and silicon electric steels [15].

Table 2 summarizes the main properties of HSS forged rolls versus conventional 3%Cr

Roll grade	Tempering (°C)	Matrix hardness (HV)	Carbide hardness (HV)	Residual stress (MPa)
3%Cr 5%Cr	120 to 140	780 to 830	1000 to 1500	-700 to -1200
Forged HSS	480 to 500	780 to 820	1500 to 3000	-300 to -400

to 5%Cr forged rolls.

Table 2. Properties of HSS forged rolls versus conventional forged rolls.

The microstructures of these HSS forged rolls consist of tempered martensite at high temperature (480°C / 500°C) to obtain a matrix hardness of 780 / 820 Vickers (Hv) with secondary precipitation of very hard MC and M_2C carbides (1500 to 3000 Hv). The heat treatments applied during the manufacturing process allow to obtain on HSS rolls low internal stresses and residual austenite.

The specific properties of HSS forged rolls lead to several advantages when used in cold rolling mills:

-Very high resistance to indentation combined with an extremely high resistance to thermal cracks and damage induced by mill incidents like strip breakage, cobles or pinches, resulting from the high hardness level along with the low level of residual austenite and residual stress [16].

-Less crack propagation resulting in less stock removal associated with mill incidents.

-A higher degree of safety compared to conventional grades due to low retained austenite and low residual stress.
-Very high retention of roughness developed during grinding and maintained during operation in the rolling mill enabling extended campaigns lengths, along with the elimination of hard face chrome plating of the roll surface.

-An overall decrease in the amount of stock removal when grinding is required.

-Increase retention of roughness is achieved when EDT is applied for last stand of a cold mill and temper/skin pass mills.

3.4.2 Implementation in cold reduction mills for automotive sheet

This chapter summarizes the up-to-date results obtained in four stands and five stands tandem cold mills for automotive sheet where the HSS forged rolls are presently used in qualification stage without chrome plating.

Table 3 resumes the cascading and chroming policy in a four stands tandem cold mill with roll diameters and specified roughness Ra.

Stand N°	WR dia. mm	Ra µm	Organic Grinding Wheel	Chrome plating
4	563 - 587	4.00 ± 0.2	EDT	No
	570 - 587	0.36 ± 0.05	Grain 70/100	No
3	536 - 563	0.56 ± 0.05	Grain 70/100	Yes
2	520 - 536	0.56 ± 0.05	Grain 70/100	Yes
1	497 - 520	0.98 ± 0.13	Grain 70/100	Yes

Table 3. Grinding, chroming and cascading policy in a four stands tandem cold mill for automotive sheet

Grinding trials:

Grinding trials with different wheel manufacturers and different types of wheel have been performed in an industrial roll shop.

The target was to grind all types of forged roll grades (from standard 3 to 5%Cr up to semi HSS and HSS grades) without grinding defects such as chattering's, feeding lines and scratches while keeping the same roughness topography than the standard rolls working in the various stands of the tandem mill. The final objective was to cover with the same grinding wheel the whole range of roughness Ra usually specified in the cold mill stands and temper mills, i.e. roughness Ra between 0.3 to 1.2 µm.

During these grinding tests, in addition of visual inspection of roll surface to detect superficial prohibitive grinding defects, surface roughness topography of the rolls has been checked using the two investigation methods: mechanical 2D roughness and optical 3D roughness.

The grinding trials performed in-situ have allowed to select a new conception of wheel able to meet the above objectives (figure 12).

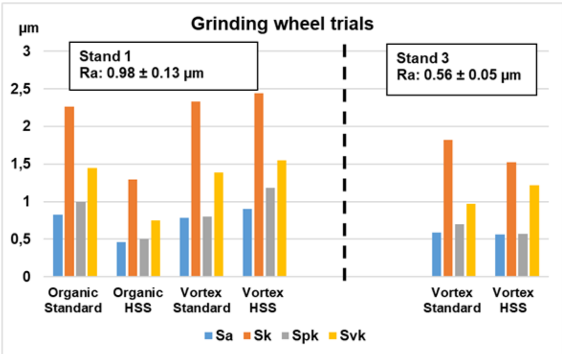

Figure 12. Influence of the grinding wheel type for grinding standard and HSS forged rolls.

Special organic wheels (Vortex) with premium ceramic grains have allowed to grind the standard forged 3 to 5% chromium and forged HSS rolls in the same roughness range with the same wheel and without any grinding defects, independently of the type of roll grinding machine (i.e. not necessarily equipped with latest designs of mechanical systems and automated operated systems) [17].

Moreover, vitrified porous bond wheels allow also to meet roll shop expectations but need new programming grinding sequence.

Rolling in last stands (stands 3 to 5):

In these stands, consistent performance has been achieved using forged HSS rolls as ground: elimination of chrome plating without affecting rolled sheet cleanliness, 2 to 3 times less stock removal and 2 to 3 times longer campaigns, introducing free rolling, also rolling AHSS steel.

As an example, figure 11 shows the roughness topography evolution on standard rolls chrome plated and HSS forged rolls before and after rolling in stand 3 of a four stands cold rolling mill for automotive sheet.

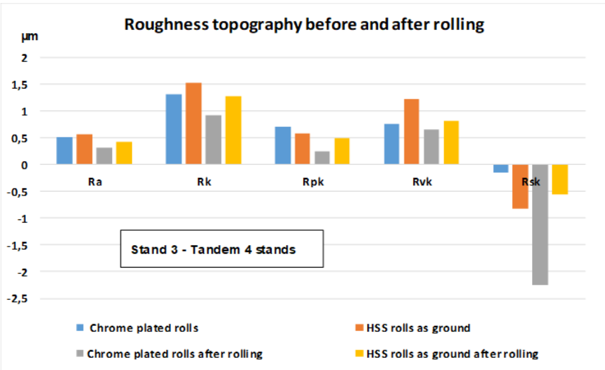

Figure 13. Evolution of roughness topography of chrome plated rolls and HSS rolls as ground after rolling in stand 3 of a four stands Tandem mill.

HSS forged rolls have been used in this stand without chrome plating: No effect on rolled sheet cleanliness was detected during rolling. After a standard rolling mill campaign, no significant deterioration of the surface topography of HSS forged rolls was observed on the contrary of standard chrome plated rolls where an important wear of peaks (Rpk) and decreasing of valley depths (Rvk) were noted: this observation suggested that the HSS forged rolls non chrome plated could stay longer in this stand than standard chrome plated forged rolls without deteriorating the rolled sheet quality.

Rolling in early stands (stands 1 and 2):

In these stands, the use of forged HSS rolls as ground with conventional organic wheel have led to a deterioration of sheet cleanliness around 10 to 15%: this was already observed at a higher degradation degree when using standard forged rolls not chrome plated.

Analysis of the rolled sheet surfaces by Scanning Electron Microscopy (SEM) have shown that the lubrication regime during rolling was closer to boundary lubrication regime with high friction coefficient: this explained the formation of iron fines and the deterioration of sheet cleanliness during rolling.

Keeping high roughness value Ra (0.8 to 1.2 µm) necessary in stand 1 to avoid skidding, friction coefficient can be reduced by modifying the surface roughness topography in order to reach:

- Rk (Sk) >
- Rvk (Svk) > Rpk (Spk)
- Rsk (Ssk) negative <<

This specific roughness topography allows a sufficient stocking of lubricant during cold rolling in order to ensure a continuous lubrication without formation of iron fines and therefore without deterioration of rolled sheet cleanliness.

Therefore, in order to suppress the chrome plating process for early stands when using HSS forged rolls as ground while keeping a high cleanliness level on the rolled sheet, it is necessary to obtain by grinding a specific surface roughness morphology which promotes "deep" valleys to the detriment of peaks, leading to a roll surface capable to retain / trap oil in the valleys while peaks are minimized reducing the abrasive effect in the roll bite and consecutively the amount of iron fines produced.

There are promising grinding wheel technologies to reach this objective [17]:
- Vitrified bond monolithic construction wheel with micro-structured ceramic grains.
- Special organic bond wheel with premium ceramic 3D grain spacing configuration.
- Special organic bond wheel with premium+ ceramic 3D grain spacing configuration.

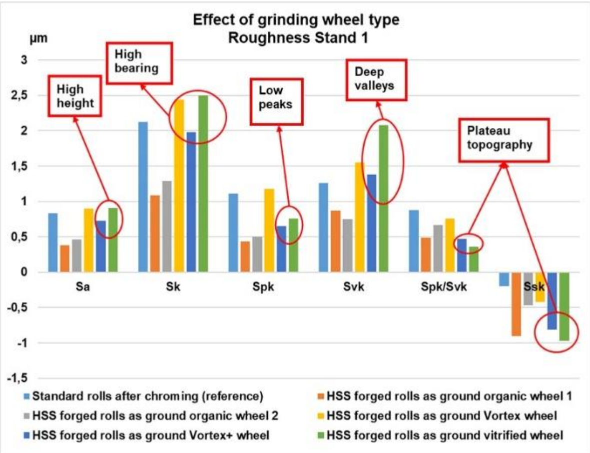

Figure 14. Effect of grinding wheel type on roughness topography.

As shown in figure 14, when grinding HSS forged rolls with vitrified wheel and Vortex type wheels, a mean height of surface topography Sa of 0.7 to 1.0 µm is obtained in the roughness specification for the first stand of a cold tandem mill. Moreover, for vitrified and Vortex+ wheels, the ratio Spk/Svk is still lower than the ratio observed on Chrome plated rolls with a plateau configuration (negative skewness Rsk).
Using HSS forged rolls in early stands as ground with this specific roughness topography should lead to a good behavior in terms of rolled sheet cleanliness and therefore should allow to suppress the chrome plating operation for these stands.

Trials in early stands of specific cold mills when batch annealing with no cleaning line are ongoing to qualify the HSS forged rolls ground to the specific roughness topography and used without chrome plating; follow up of mill parameters are made in terms of rolling force, forward slip, rolling speed, reduction, friction coefficient combined with measurements of cleanliness on the rolled sheet and roughness topography evolution during rolling.

The influence of the cooling system and emulsion type has to be considered in this implementation [18].
Moreover, other process texturing methods such as etching and EDT texturing are also taken into consideration to generate ideal surface morphology on the HSS forged work rolls.

4 CONCLUSION

HSS forged rolls are presently used in the various stands (early and lasts stands) of more and more cold rolling mills for automotive sheet.

These HSS forged rolls allow to suppress definitively the chrome plating operation without changing the mill regulation parameters while giving excellent performances in terms of campaign lengths and roll consumption (significant improvement of TCO benefits).

Grinding wheel developments along with adapted grinding practices have driven the success of achieving required surface roughness, critical surface aspects and surface cleanliness of the rolled sheet finish.

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